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TERRAIN MODELLING USING THE SPLIT-STEP PARABOLIC EQUATION METHOD

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INTRODUCTION

There are currently several software programs that model radiowave propagation over irregular terrain. These models use a combination of spherical earth diffraction, multiple knife-edge diffraction, wedge-diffraction, and geometrical optics to arrive at a solution for the field for a given transmitter/receiver geometry and a specified terrain path. More recently, parabolic equation (PE) methods have been applied to model propagation over terrain, such as that developed by Levy (1).

The most familiar or well-known of these models is the Longley-Rice model (2). This model was designed for low-altitude propagation and works fairly well for diffraction and near-diffraction regions. A site-specific propagation model for general terrain, called SEKE, was developed at Lincoln Laboratory, Ayasli (3). This model is based on the assumption that the propagation loss over any path (in the frequency range from VHF to X-band) can be approximated by one of the multipath, multiple knife-edge diffraction, or spherical earth diffraction losses alone, or a weighted average of these three basic losses. Another model, developed at Ohio State University, Luebbers (4), is based on the geometrical theory of diffraction (GTD) and works by determining the existing rays, for a given height/receiver geometry and terrain profile, from a family of 16 ray types. The total field at the target is then found by adding the ray amplitudes from each possible ray.

Each of these models has various limitations, but the main limitation they all share, with the exception of the PE model, is the inability to handle ducting or non-standard range-dependent environmental conditions. SEKE allows a variable earth radius factor, but this assumes a constant gradient and horizontal homogeneity. Some of the literature regarding GTD has stated that this method can be extended to inhomogeneous media, but this author has not seen any published results for such cases.

The PE model from (1), called FDPEM (Finite Difference Parabolic Equation Model) is able to handle range-dependent, ducting conditions. As the name implies, it solves the parabolic equation by using finite difference techniques. However, computationally, finite difference methods can be time consuming.

This paper presents an efficient method by which one can determine the field at any point above the earth's surface in the presence of range-dependent atmospheric conditions. The model is based on the split-step Fourier algorithm developed by Hardin and Tappert (5) to solve the parabolic equation. Comparisons are made against measured data and the above mentioned models.

MODEL DESCRIPTION

The application of the split-step method to model tropospheric radiowave propagation over the ocean has been well documented (6),(7). The problem becomes somewhat more complicated when applying this same technique to model radiowave propagation over irregular terrain.

In the following formulation, the atmosphere is assumed to vary in range and height only, making the field equations independent of azimuth. Beginning with the parabolic equation derived by Fock and after making the envelope transformation (8), the equation that must be solved is

$$\frac{\partial^2\psi}{\partial z^2} + 2ik_o\frac{\partial\psi}{\partial x} + k_o^2(n^2-1)\psi = 0 \qquad (1)$$

where k_o is the free-space wavenumber, n is the index of refraction, ψ represents a scalar component of the electric field, and x and z are the spatial cartesian coordinates corresponding to range and height, respectively.

For propagation over terrain, and assuming horizontal polarization, equ. (1) is subject to the range-dependent boundary condition, $\psi(x, z=f(x)) = 0$, where $f(x)$ is a general function describing the terrain. A transformation is made according to Beilis and Tappert (9), which generalizes the "earth curvature" transformation, and effectively maps the range-dependent "terrain" coordinate system to a flat or smooth earth coordinate system. This results in a "modified" parabolic equation subject to the simpler boundary condition that the field vanishes at the surface - which is now range-independent in the new coordinate system. This problem can then be easily solved by using the split-step method as described in (6).

The transformation is made by introducing a change of variables. Let

$$\hat{x} = x$$
$$\hat{z} = z - f(x)$$

where

$$f(x) = t(x) - \frac{x^2}{2a}$$

and define the scalar component of the field in terms of the new coordinate system:

$$\psi(x,z) = \hat{\psi}(\hat{x},\hat{z})e^{i\theta(\hat{x},\hat{z})}. \qquad (2)$$

The function $t(x)$ describes the actual terrain and can be any digitized set of height/range points. $x^2/2a$ (where a is the earth's radius) takes into account the earth's curvature.

Substitution of equ. (2) into equ. (1) yields the modified parabolic equation

$$
\begin{aligned}
&\frac{\partial^2 \hat{\psi}}{\partial \hat{z}^2} + 2ik_0 \frac{\partial \hat{\psi}}{\partial \hat{x}} + k_0^2(\tilde{n}^2 - 1) = 0 \\
&\tilde{n}^2 = n^2(\hat{z} + t(x)) + 2\hat{z}\left(t''(x) + \frac{1}{a}\right)
\end{aligned}
\qquad (3)
$$

with the new boundary condition, $\hat{\psi}(\hat{x},0) = 0$. $t''(x)$ in equ. (3) represents the second partial derivative with respect to x. Notice in comparing equ. (3) with equ. (1), the inclusion of an arbitrary terrain has effectively produced a "new" modified refractive index. This is consistent with the modified refractivity, or M-unit, normally used in tropospheric wave propagation over the ocean, which was derived to take into account the earth's curvature. The split-step Fourier method is then applied to give the solution of the field at discrete range steps for all target heights under consideration.

This method offers a numerically efficient, full wave solution to the field because of the implementation of the Fast Fourier Transform (FFT) in the computer model. Computer execution times increase for increasing frequency and/or large propagation angles, i.e., steep terrain slopes. However, the split-step method remains more efficient than finite difference techniques for these extreme cases.

RESULTS

Figures 1 and 2 show comparisons between measured data and the Terrain Parabolic Equation Model (TPEM). The results are displayed as height versus propagation factor (or field strength relative to free space) in dB, with "height" referring to height above the ground at the particular receiver range shown. The terrain profile is also shown for each case. For both figures the environment was assumed to be a homogeneous standard atmosphere. The data shown in Fig. 1 were taken from ref. (2). Results from the model SEKE are also shown. Data from ref. (3) are shown in Fig. 2 along with results from the GTD and the Longley-Rice model. In both figures TPEM agrees very well with the measured data and the other models.

In 1946, the Navy Electronics Laboratory (now Naval Command, Control and Ocean Surveillance Center) conducted an experiment over the Arizona desert to study atmospheric inhomogeneity and the irregularity of the terrain (10). The transmitter was located at Gila Bend with a receiving station at Sentinel. This site was chosen because of the large diurnal variation in surface temperature common in the desert, leading to strong inhomogeneous ducting conditions. Meteorological measurements were taken at the transmitting and receiving stations, and at two stations along the path. The terrain profile and the meteorological measurements for 0300 February 6, 1946 (plotted as height versus M-units) are shown in Figure 3. Arrows indicate the location of the measuring stations and the "0" heights on the refractivity scales correspond to the local ground surface. Figure 4 shows the measured data along with that predicted by TPEM for both the actual terrain and the smooth earth case. As the figure shows, one must also take into account the actual terrain as well as the environment to make proper field predictions.

To demonstrate the power of the split-step method, a coverage diagram is shown in Figure 5 for a homogeneous, elevated duct environment over East Anglia. Propagation loss is indicated by the different gray shades and the antenna is located 45 meters above the ground.

Since equ. (3) does not allow for propagation over vertical obstacles, such as cliffs or buildings ($t''(x)$ will be undefined for such cases), a special case can be made by simply eliminating the field immediately adjacent to such obstacles and propagating the field forward as usual. This does not violate any conditions in the split-step model as the PE approximation inherently neglects backscatter. Figure 6 shows a coverage diagram for such a case. Excellent agreement was found when compared against FDPEM.

CONCLUSIONS

A numerically efficient method has been presented to model tropospheric radiowave propagation over irregular terrain in the presence of range-dependent non-standard environmental conditions. Results from this model were compared against measured data and other existing models and was shown to give excellent agreement. This work is in the public domain.

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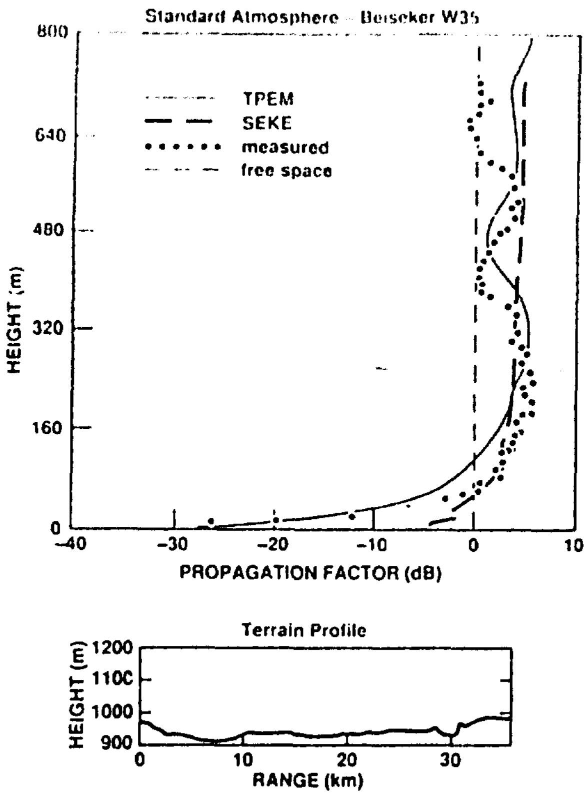

Figure 1. Comparison between TPEM, SEKE, and measured data at 167 MHz for standard atmosphere over the terrain shown. Transmitter height is at 18.3 meters above the ground at 0 range. Receiver range is at 35.5 km.

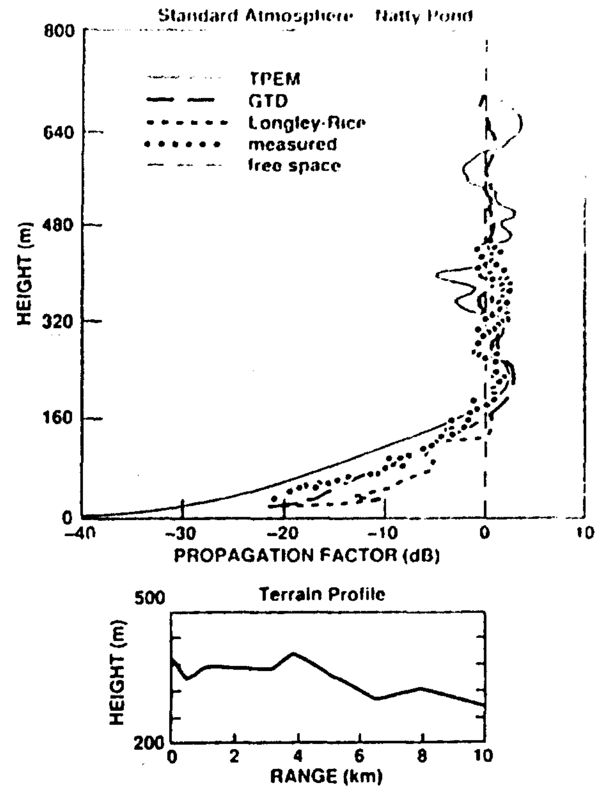

Figure 2. Comparison between TPEM, GTD, Longley-Rice, and measured data at 110.6 MHz for standard atmosphere over the terrain shown. Transmitter height is at 1.36 meters above ground at 0 range. Receiver range is at 6.6 km.

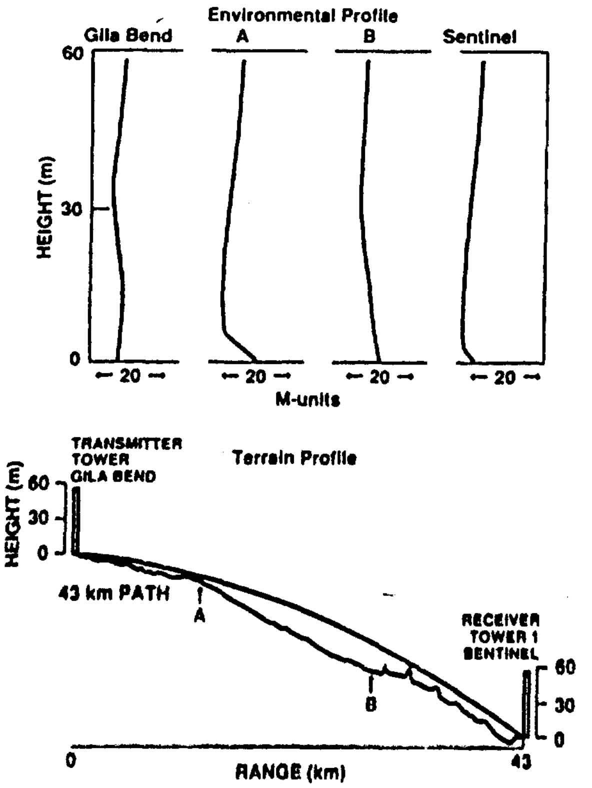

Figure 3. Terrain and environmental profiles for Figure 4. Arrows indicate location of meteorological measurements.

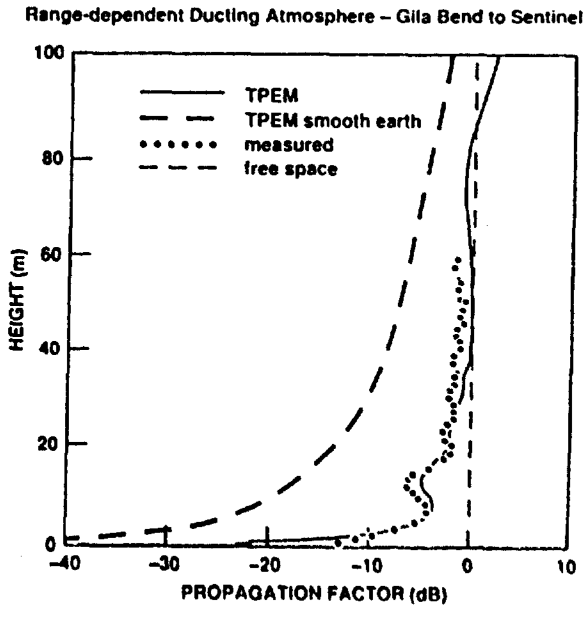

Figure 4. Comparison between TPEM for actual terrain, TPEM for smooth earth, and measured data.

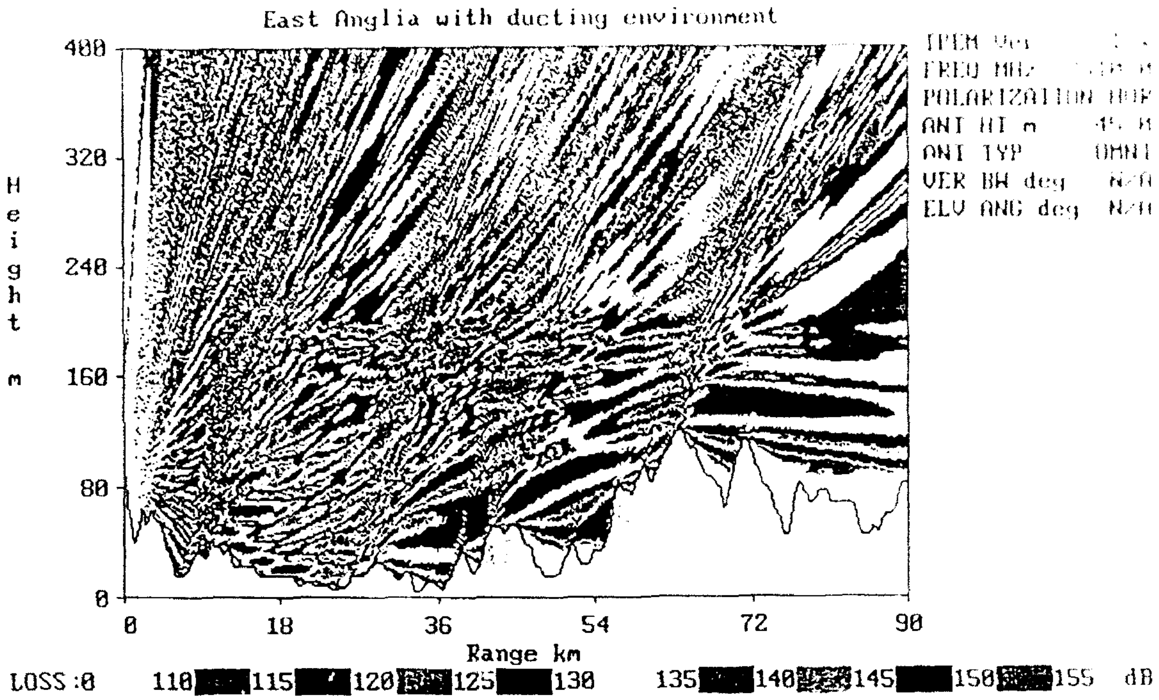

Figure 5. Coverage diagram with homogeneous elevated duct. Antenna height is 45 m above the ground at 0 range.

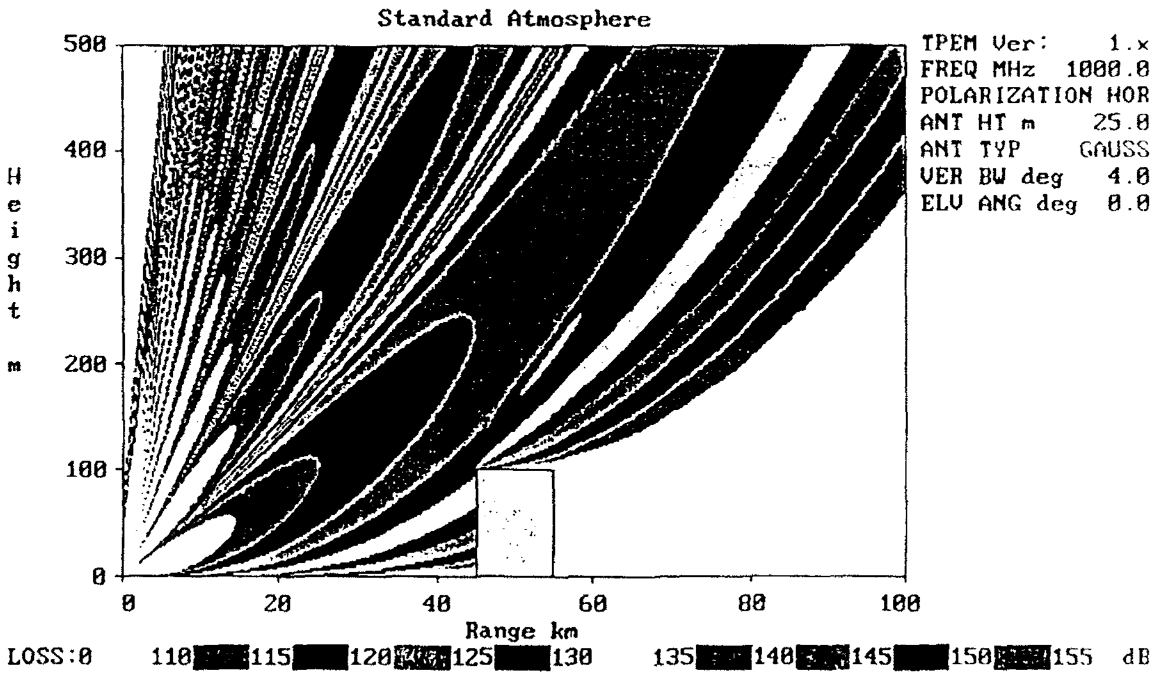

Figure 6. Coverage diagram for flat topped block centered at 50 km.